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ORIGINAL RESEARCH

Experimental investigation of CNG and gasoline fuels combination on a 1.7 L bi-fuel turbocharged engine

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Abstract In this paper, the potential of combined injection of CNG and gasoline is studied on a 1.7 L turbocharged, port-injected SI engine and the best engine performance point for the best conversion efficiency of the catalytic converters has been investigated. Compressed natural gas (CNG) as an alternative fuel is used in spark ignition engines to improve fuel consumption and exhaust emissions. The improvements gave more advantage in emission but it lowered the performance of the engine. As a substitute, CNG has a higher octane number and knocking resistance than gasoline and hence CNG-dedicated engines can have higher compression ratios and therefore higher indicated efficiencies. Turbocharged bi-fuel, combined CNG and gasoline, injection engine of is a new concept which offers direct benefits with regards to gas or gasoline powered vehicles running separately on each fuels. It also opens very interesting perspectives for meeting future emission regulations using only a three-way catalyst, since the stoichiometry condition of combustion is maintained over the whole engine operating range. Results show that the combined injection of gasoline and CNG is much better than gasoline mode in terms of fuel consumption and raw HC and CO emissions. However, as expected the NO_x emission will increase. According to the obtained results at 16.2 bar BMEP, 3000 rpm full load condition with 30% CNG mass fraction, the BSFC, CO and HC emissions are improved by 16, 66 and 50%, respectively, compared to gasoline single mode. It was found that a fuel mixture of 30% CNG mass fraction was the best trade-off point between engine performance and emission production. Also, significant reductions of fuel consumption were observed. Full-load tests carried out with a turbocharged engine enhanced the synergy effect between the two fuels at full-load condition.

Keywords Turbocharged SI engine · CNG · Fuels' combination · Exhaust emission

Introduction

Compressed natural gas (CNG) is an alternative fuel, which can be used as a replacement for gasoline, diesel, or propane fuel. This alternative fuel has many advantages in environmental and air pollution control [1]. It is considered to be an environmentally "clean" alternative to those fuels and it is much safer in the event of a fuel leakage. Natural gas is lighter than air, so it disperses quickly when leaked or spilled [2]. The utilization of full potential of CNG as an alternative fuel is a means of reducing exhaust emissions. It is made by compressing natural gas (mainly methane) [3]. It has been found that for engines running on CNG, with precise *A*/*F* ratio control and special catalysts for CNG exhaust gas, the California SULEV[1] exhaust emission

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[1] Super ultra-low emission vehicle.

standards were met [4]. The advantages of CNG as fuel have already been highlighted by a number of studies; CNG as an interesting alternative to liquid fossil fuels reduces the CO_2 emissions and provides a clean energy sources for transportation [5, 6].

The drawback of the use of CNG in the engines is its lower flame speed that results in higher temperature of engine components. Moreover, the low volumetric efficiency and energy density of CNG reduces the engine output torque in naturally aspirated engines [4].

The bi-fuel spark ignition engines already on the market are equipped with independent gas and liquid fuel injection systems. They can operate either with gas or liquid fuel but they do not fully exploit the potential of each fuel. This novel injection strategy was reported in the early 2000s and consists of injection of a gaseous fuel such as CNG having a high octane number, with a liquid fuel such as gasoline with a high energy density, during the same engine cycle, in order to get the most of both fuels' advantages.

A turbocharged engine produces more overall power than the same naturally aspirated engine. This can significantly improve the power-to-weight ratio for the engine. The turbine extracts wasted kinetic and thermal energy from the high-temperature exhaust gas flow and produces the power to drive the compressor, at the cost of a slight increase in pumping losses. Also, the use of CNG in spark ignition turbocharged engine offers other advantages such as high knocking resistance and higher specific power outputs. On the other hand, compared to gasoline-fuelled engine, for naturally aspirated CNG-fuelled engines the volumetric efficiency is decreased by about 4–10% due to its lower energy density, reducing the engine output torque. In addition the possibility of deposit formation on the surface of intake valves is higher since the cleaning effect of gasoline does not exist. The lower flame speed of CNG also results in higher temperature of engine components.

Pipitone and Beccari [7] investigated the effects of combined injection of gasoline and CNG in a naturally aspirated spark ignition engine with injection of gasoline and CNG in the intake manifold. They studied the knock tendency of the mixed fuel and concluded that it is lower than for gasoline and the spark timing is less retarded. Advanced ignition timing and the stoichiometric air/fuel ratio lead to thermal efficiency improvement of about 10–27% as compared to the gasoline mode.

Delpech et al. [8] investigated the effects of combined injection of gasoline and methane in a turbocharged spark ignition engine with injection of gasoline and methane in the intake manifold. They increased the compression ratio of the basic engine from 9.5 to 11.5. It was concluded that because of higher thermal efficiency with respect to gasoline mode and higher volumetric efficiency with respect to CNG mode, output torque is higher for the combined injection case.

Obiols et al. [9] investigated the effects of gasoline and CNG mixed injection in a turbocharged spark ignition engine with direct injection of gasoline inside cylinders and port injection of CNG in the intake manifold. They strengthened valve seats for erosion prevention at high thermal loads. They concluded that with the combined injection of gasoline and CNG, the engine output torque is higher than that of gasoline and CNG modes.

Momeni Movahed et al. [10] performed an experimental study on a turbocharged engine. They indicated how some problems of gasoline mode such as retarded ignition timings for knock prevention and rich air–fuel mixture for component protection can be resolved with the combined injection of gasoline and CNG. Results clearly show that the combined injection improves thermal efficiency compared to gasoline mode. On the other hand, some problems of CNG mode such as high cylinder pressure and heat loss to the engine coolant can be solved in the simultaneous injection of gasoline and CNG.

Dashti et al. [11] have carried out a thermodynamic cycle simulation of a conventional four-stroke SI engine using gasoline and CNG fuels to predict the engine performance and emissions. The first law of thermodynamics was applied to determine in-cylinder temperature and pressure as a function of crank angle. The results of this work were evaluated using corresponding experimental data of an existing SI engine running on both gasoline and CNG. The results showed that the power of CNG-fuelled engine is lower than that of gasoline-fuelled engine by about 11% over the speed range 1500–4000 rpm due to higher volumetric efficiency. On average, when the engine operates with CNG fuel, the ISFC is reduced roughly by 16% over this speed range. However, for this engine speed range, the specific emissions of CO_2, CO and concentration of UHC are decreased considerably by about 33, 60 and 53%, respectively, while NO concentration is increased by 50%.

Baloo et al. [12, 13] carried out experiments for binary blends of methane/iso-octane and CNG/iso-octane. In this study, methane (main component of CNG) was added in two volumetric fractions of 30 and 70% to iso-octane (representative fuel of gasoline). The results showed that addition of methane to iso-octane increases the unstretched propagation speed in lean region but decreases the unstretched propagation speed in rich region.

Recent research proves that concomitant injection of gas and liquid fuel in SI engines can lead to strong synergies between the two fuels. However, in these studies the main focus has been on performance, torque and thermal efficiencies of the engines. The potential of concomitant injection of CNG and gasoline on a four-cylinder 1.7 L turbocharged Gasoline Port Injection engine is investigated in this paper. Finding the best point for the performance as

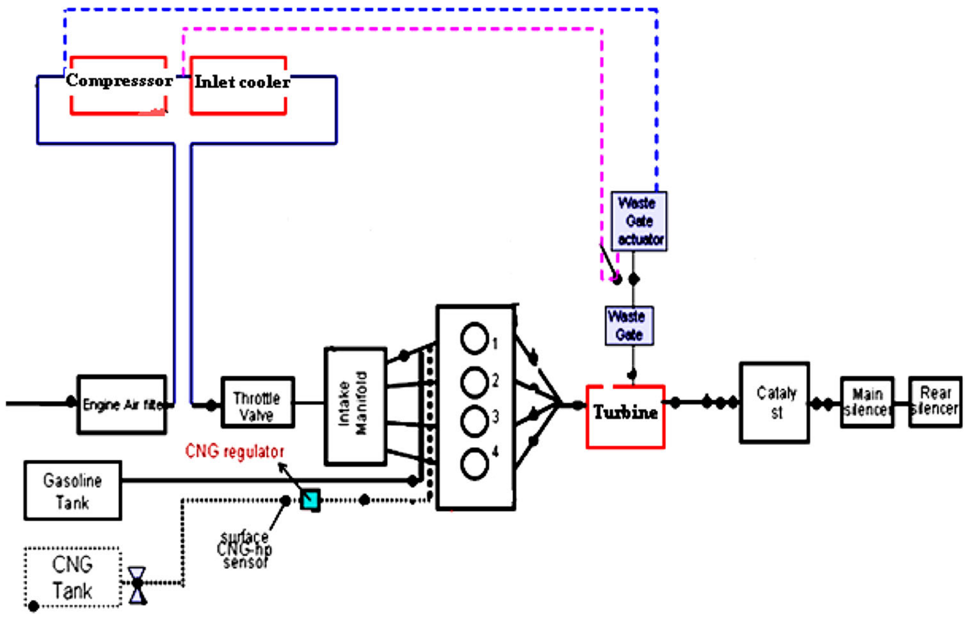

Fig. 1 Schematic diagram of the turbocharged bi-fuel engine and related control devices

Table 1 The 1.7 L TC engine specification

Item	Value	Item	Value	Item	Specification
Bore (mm)	78.6	Max. power (kW)	110	Concept	Turbo charging
Stroke (mm)	85	Speed at max. power (rpm)	5500	Compressor type	Centrifugal compressor
Displacement (cm^3)	1650	Max. torque (Nm)	215	Turbine	Single entry
Bore distance (mm)	84	Speed at max. torque (rpm)	2200–4800	Boost control	Waste gate

well as emissions production and catalyst conversion efficiency is the main focus of this study.

The trade-off between the engine performance and exhaust gas pollution is important because in the automotive industry, the development cycles are continuously reduced and the guidelines of the legislation concerning the pollutant emission limits become more restrictive [5]. The legislatively enforced emission limits can only be fulfilled by the optimization of the exhaust gas system. This study investigates the potential of combined injection as compared to the gasoline and CNG operation to find the best point of trade-off between performance and emissions, which is the state of the art in this field of research.

Experiments and testing

Experimental setup

The engine used in this study was a four-cylinder, four-valves per cylinder, 1.7 L port-fuel injection turbocharged engine with a return-less fuel line. Figure 1 shows a schematic diagram of different components used in the engine and different related control functions. Table 1 indicates the specification of the engine which has been used for tests.

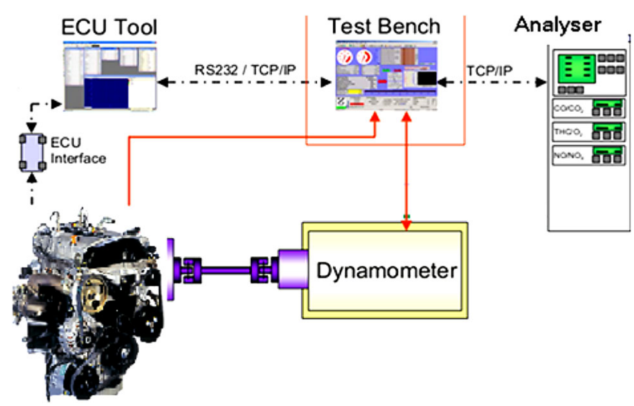

Fig. 2 Schematic diagram of the engine and experimental setup of control devices

The engine is coupled to an AVL eddy current absorbing dynamometer type APA 1F4-E-0509 with the maximum power of 120 kW and maximum speed of 8000 rpm. The schematic diagram of the engine and different control devices of the test setup are shown in Fig. 2. The engine data acquisition is done by the ECU tools and test bench

Table 2 The dynamometer and test devices specification

1. Dynamometer

Dyno. type	Max torque (Nm)	Max speed (rpm)	Max power (kW)	Inertia (kg m^2)	Weight (kg)
AVL APA 1F4-E-0509	509	8000	120	0.35	600

2. Fuel temperature control

Model	Stability (°C)	Fuel temp. outlet (°C)	Fuel temp. inlet (°C)	Ambient temp. (°C)
AVL 753C	Better than 0.02	10–80	−8 to +70	5–50

3. CNG consumption measuring device

Model	Fuel type	Transmitter	Nominal flow (kg/h)	Maximum flow (kg/h)	Zero stability (kg/h)	Density accuracy (kg/m^3)	Temp. accuracy (C)
Emerson CMF010	Liquid	1700/2700	0–82	108	0.002	2	1 + 0.5%
Emerson CMF010	Gas	1700/2701	0–32	65	0.002	–	1 + 0.5%

4. AFR analyzer device

Model	Measuring	Impedance (Ω)	Ambient temp. (°C)	Humidity (%)	Gas temp. (°C)
IPCO DHBS102	0.7–1.4	0–174	5–45	less than 80	–7 to 900

monitoring. INCA[2] software was used to record and analyze measured data from the control unit and the engine in parallel. The program helps to determine measured engine data such as lambda, different temperatures and voltage values, etc. The test bench monitoring system is essential to control engine various necessary parameters such as cooling temperature, oil pressure and temperature, fuel supply, intake air and exhaust flow characteristics.

The engine is essentially controlled by an original equipment manufacturer (OEM) engine control unit (ECU). The ECU modulates the air/fuel ratio around stoichiometric at a certain frequency and amplitude based on the feedback from an upstream heated exhaust gas oxygen (HEGO) sensor. The input air is mixed by gasoline and CNG with a desired air/fuel ratio and CNG mass fraction. Combustion of the mixture creates exhaust gases with high pressure and temperature that enter the turbine. The rotational speed of the turbine is controlled by a waste gate that allows bypassing of the exhaust gas from the turbine.

Table 2 shows the specifications of dynamometer and measuring devices of the test. CNG consumption is measured using an Emerson CMF010 Coriolis type mass flow meter. Cylinder pressures are measured and recorded in all cylinders with four AVL GH12D pressure transducers. Important exhaust emissions are measured using Horiba MEXA-7000 analyzers.

2 ETAS GmbH, Stuttgart, Germany.

Testing procedure

Dedicated gasoline and CNG performance test

In order to compare the engine performance in gasoline and CNG modes, full-load tests at different engine speeds are done. In the first part of this study, the test results are investigated in gasoline and CNG-dedicated fuel modes. The results are shown in Fig. 3. At this figure BMEP[3] and BSFC[4] of the engine for both gasoline and CNG fuels at WOT[5] from 1000 to 5500 rpm are shown.The BSFC values are calculated according to Eq. (1) [10]:

$$\text{BSFC (g/kw h)} = 1000 \times \frac{m_{\text{Gasoline}}\left(\frac{\text{kg}}{\text{h}}\right) + m_{\text{CNG}}\left(\frac{\text{kg}}{\text{h}}\right) \times \frac{\text{LHV\_CNG}}{\text{LHV\_Gasoline}}}{\text{Engine power}}, \quad (1)$$

Lower heating value (LHV) of the global fuel introduced into the combustion chamber (mixture of gasoline and gas) was calculated linearly from the mass flow rate measurements of each single fuel. Table 3 shows CNG fuel specifications measured according to ASTM standard.

Normally the BMEP of CNG is 4–14% less than that of gasoline throughout all the engine speeds. [14] This is due

3 Brake Mean Effective Pressure.

4 Brake Specific Fuel Consumption.

5 Wide Open Throttle.

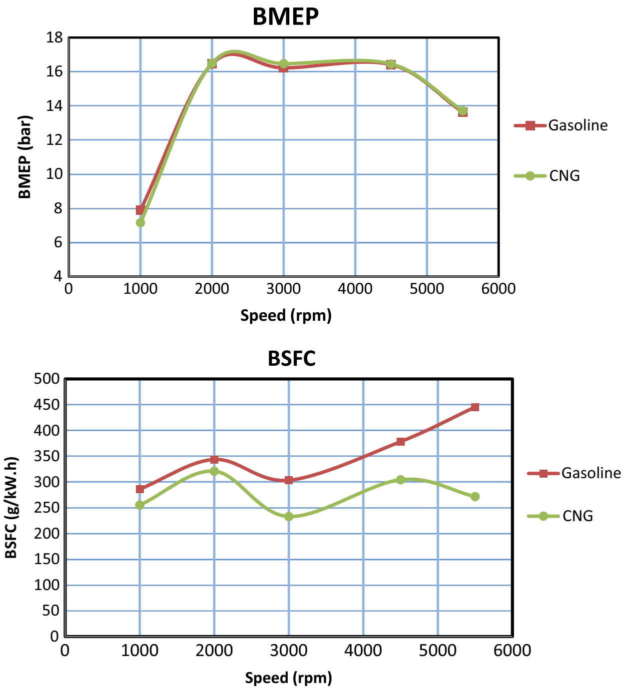

Fig. 3 The performance curves of the engine at gasoline and CNG-dedicated modes

to the lower flame speed of CNG compared to gasoline. As a result, a bigger fraction of negative work is found in CNG operation. To solve this problem, advancing spark timing could be used for the CNG operation because in CNG mode the knock resistance of CNG is much higher than for gasoline.

In addition, the displacement of air by CNG in the cylinder reduces the volumetric efficiency and consequently causes the BMEP loss. Normally in the case of CNG the power will decrease but to make the plausible comparison of this study by the spark advancing and leaner combustion in CNG mode the BMEP, which is the index of engine power, was maintained equal at all speeds as shown in the Fig. 3.

On average, CNG produces 10% less indicated power and indicated torque compared to gasoline. This is mainly due to lower charge energy of CNG that reduces the volumetric efficiency of engine during induction stroke. Greater indicated power reduction of CNG was found at higher engine speed due to the inherently slower flame speed of CNG as compared to gasoline.

The corrected BSFC behavior at different engine speeds is shown in Fig. 3. CNG results in a remarkably 11–39% lower fuel consumption compared to gasoline. The minimum BSFC of gasoline and CNG are 300 and 235 g/kw h at 3000 rpm. This can be explained by the facts that heating value of CNG is 12% higher than that of gasoline and it produces a comparable but lower output indicated power, therefore CNG consumes less energy per unit power produced compared to gasoline under the same engine operations. The figure also shows that the minimum BSFC occurs at medium engine speeds. At low engine speeds, BSFC values are higher because of higher heat transfer contribution. At high engine speeds, BSFC values are higher because of higher engine friction.

At the rpm over 4500 it is seen that the BSFC of the CNG decreased. The reason is that in the CNG mode, the mixture could be leaner because of CNG higher knock resistance, while for the gasoline the fuel would be rich to protect engine from knocking and higher exhaust temperature.

The exhaust emissions of HC, CO and NO_x for both fuels are presented in Fig. 4. Results shows that CNG produces lower unburned hydrocarbon emission throughout the speed range as compared to gasoline. The emission of HC is significantly reduced by 25–72% with CNG operation due to a more complete combustion of CNG as compared to gasoline. In addition, CNG operation shows significantly lower CO emission. It was found that CNG produced 30–91% lower CO which is a result of incomplete combustion in engine and is generated when the engine is operated with a rich mixture or when proper air–fuel mixing is not achieved. With high hydrogen-to-carbon ratio and its simpler chemical structure, it is expected that CNG (predominantly CH_4) produces lower CO than gasoline. The emission of NO_x from both gasoline and CNG fuels is shown in Fig. 4. The result shows that CNG yields higher NO_x emission especially at higher engine speeds due to the higher temperature of the engine cylinder generated by CNG combustion and lower richness of air fuel mixture due to more advanced ignition timing. It means when operating on natural gas, we have greater antiknock quality, so it can maintain the exhaust gas temperature lower, so it does not need to retard the spark to avoid knock. As a result, it does not need to enrich the mixture and can maintain stoichiometry.

The combination of CNG and gasoline test

In the second part of the experimental analysis, several tests are performed with the combined injection of gasoline and CNG. These tests are done at different engine speeds and full-load condition with different CNG mass fractions. For analysis, the results at engine speed of around maximum torque (3000 rpm) are chosen in Figs. 5 and 6.

Because of mechanical restrictions of the engine, the maximum allowable power was limited. With 20% CNG mass fraction, this magnitude of the power is achieved. Therefore, at higher CNG mass fractions, the air–fuel mixture can lead to savings in fuel consumption and reduction in emission. The BSFC curve and lambda trend

Table 3 The CNG fuel specification

Sample identification: *P*: 2500 psig, *T*: °C			
No.	Component	Test method	Result
1	H_2S	ASTM D 5504	1.6 ppm
2	N_2	ASTM D 1945	3.9 mol%
3	C_1	ASTM D 1945	89.6 mol%
4	CO_2	ASTM D 1945	1.0 mol%
5	C_2	ASTM D 1945	3.6 mol%
6	C_3	ASTM D 1945	1.12 mol%
7	IC_4	ASTM D 1945	0.24 mol%
8	NC_4	ASTM D 1945	0.31 mol%
9	IC_5	ASTM D 1945	0.10 mol%
10	NC_5	ASTM D 1945	0.07 mol%
11	C_6	ASTM D 1945	0.04 mol%
12	C_7	ASTM D 1945	0.02 mol%
Total			100.0
			Results
Calculated average molecular weight (g/mol)			17.99
Calculate gas specific gravity, air = 1.000 (M. weight of air = 28.964 g/mol)			0.621
Calculate gas density in Kg/m^3 (P = 1013.25 mbar, T = 15 °C)			0.761
Calculate net calorific value (P = 1013.25 mbar, T = 15 °C)			
MJ/m^3			34.53
Btu/ft^5			922.7
Calculate gross calorific value (P = 1013.25 mbar, T = 15 °C)			
MJ/m^3			38.27
Btu/ft^3			1022.5

versus CNG mass fraction are shown in Fig. 5. Comparison with Fig. 3 shows that the BSFC of 10% CNG mass fraction is equal to the gasoline mode. Reasons for this are lower ignition timing difference and equal lambda for these two points and higher air flow rate of 10% CNG mass fraction. As shown in Fig. 5 it can be seen that increasing of CNG mass fraction, IMEP[6] standard deviation decreases because of the CNG lower heating value. Also, the lambda curve shows that the addition of CNG is being used to bring the engine back to a stoichiometric operating condition, when it would otherwise be operating with the use of enrichment if it were gasoline only. This arises as the addition of CNG increases the overall anti-knock quality of the fuel, and therefore enrichment is not required.

The combustion process in an SI engine is not repetitive from engine-cycle to engine-cycle. The peak pressure obtained can change 30% from cycle-to-cycle in a well-functioning engine. Cycle-to-cycle variations in combustion can be attributed to the cycle-to-cycle variations of any of the parameters known to affect combustion. Residual gas mass fraction, turbulence level and non-homogeneity of air–fuel mixture (droplet in mixture) are the main parameters affecting the initial flame kernel growth that finally leads to combustion variation in different cycles. By increasing the CNG amount in mixed fuel, spark advance can be increased. Therefore, the peak pressure has increasing trend as shown in Fig. 5.

Residual gas mass fraction decreases with increase of pressure and mixture homogeneity is improved with higher CNG in mixture that causes the COV to have decreasing trend Eq. (2) [15]:

$$\mathrm{COV} = \sqrt{\frac{\sum_{i=1}^{n}\left(\mathrm{IMEP}_i - \mathrm{IMEP_{mean}}\right)}{n-1}} \text{ and }$$
$$\mathrm{IMEP_{mean}} = \frac{1}{n} \times \sum_{i=1}^{n} \mathrm{IMEP}_i. \tag{2}$$

To achieve constant power the maximum in-cylinder pressure should be increased by spark advancing and more charge boosting.

[6] Indicated Mean Effective Pressure.

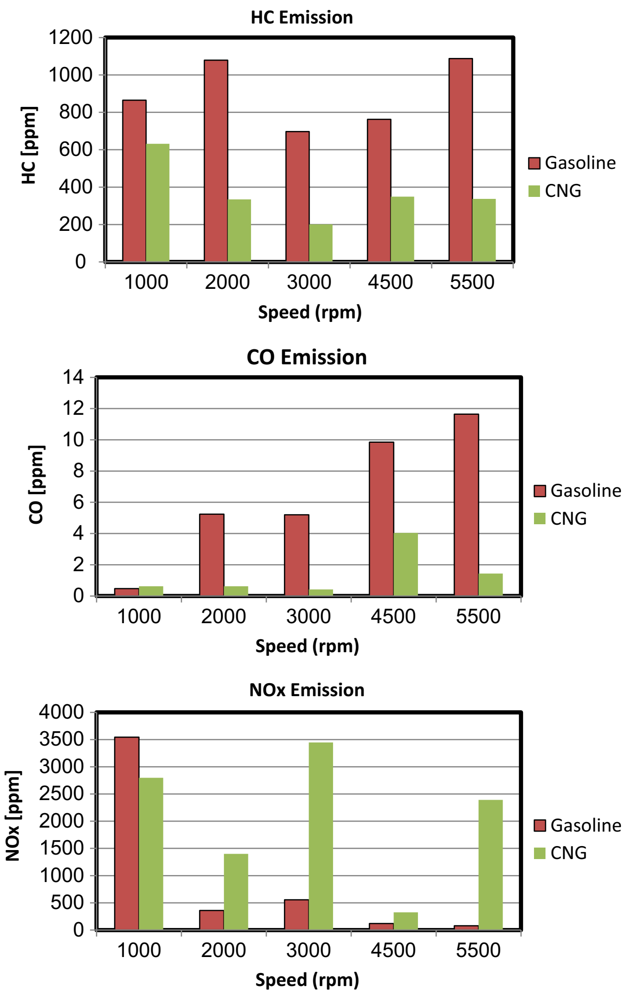

Fig. 4 The emissions of the engine at gasoline and CNG-dedicated modes

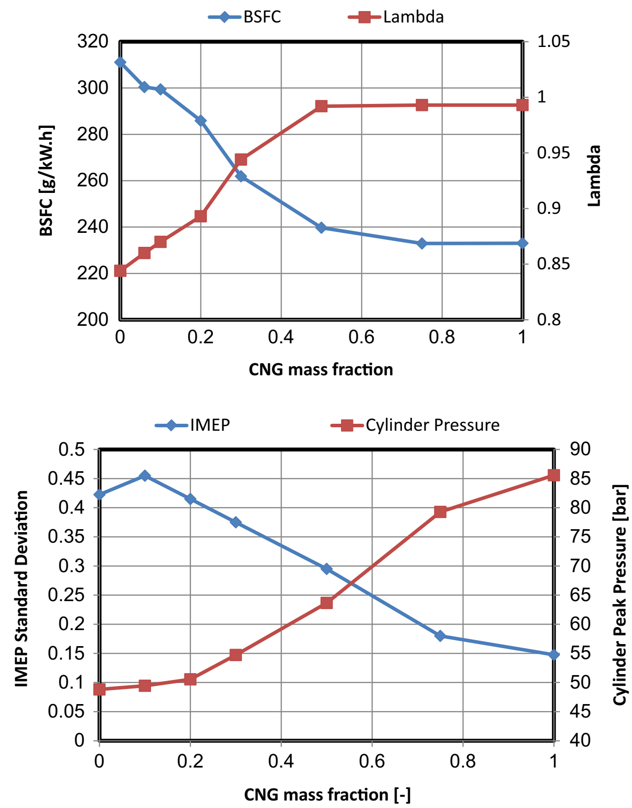

Fig. 5 The performance result of the engine at different combined fuel modes

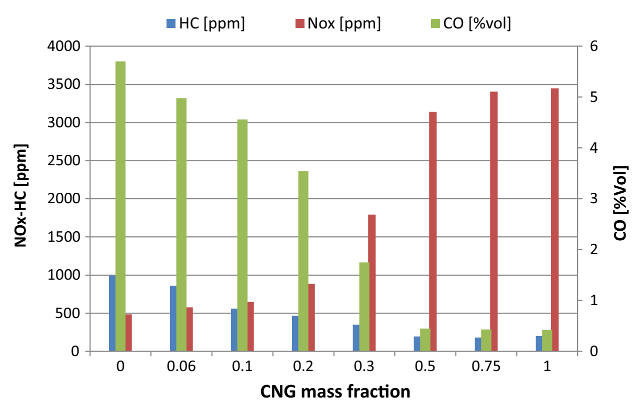

Fig. 6 The emission of the engine at different combined fuel modes

Figure 6 shows the result of emissions measurement for this case. The results show that as the CNG mass fraction increases, HC and CO emissions decrease but NO_x emission increases. The reason is that CNG has different compositions and as discussed before behaves differently than gasoline. More ignition timing advancing and closer to stoichiometric air fuel mixture causes higher NO_x emission in the higher CNG mass fraction. Therefore, the cylinder peak temperature will increase and because of adequate oxygen content in combustion the NO_x creation is enhanced.

Considering the experimental results of Fig. 6 it can be seen that for the case of 20–30% CNG mixture the best exhaust composition is achieved as total pollutants are at a minimum.

HC and CO emissions are very high with methane only because of high fuel entering limitation due to high scavenging. With gasoline addition, the gas injection duration is decreased, thus reducing the fuel entering limitation. HC emissions were minimum from 30% CNG mass fraction because the entire gas fraction could enter the cylinders. Comparing to Fig. 4 at 3000 rpm the HC and CO emissions are about half of the gasoline only mode. But, the NO_x emission is about three times.

Actually, it is very likely that with combined injection, the methane/gasoline/air mixture has a much better homogeneity than pure gasoline and air, hence a lower probability of generating unburnt hydrocarbons. These results show that an excellent trade-off between performances, fuel consumption, HC, CO and NO_x emissions can

Table 4 Comparison table between combined injection (30% CNG) and single fuel operation—3000 rpm at full load

Items	Dedicated gasoline	Dedicated CNG	Combined fuels (30% CNG)
BMEP (bar)	16.2	16.2	16.2
BSFC (g/kw h)	303.4 (+13%)	233 (−11%)	261.9
CO (ppm)	5.2 (+66%)	0.43 (−18%)	1.75
HC (ppm)	697.4 (+50%)	201.1 (−42%)	349.8
NO_x (ppm)	556.56 (−69%)	3446.9 (+48%)	1792.9

be reached for a CNG mass fraction of about 30% which are summarized in Table 4.

The table shows at dedicated CNG mode that all items have a best result expect for NO_x emission. Nevertheless benefit gained by the double-fuel combustion at full load can be considerable, since in this condition knocking danger is higher and gasoline fuelled engines run with rich mixtures; decreasing the engine load, knocking becomes less dangerous and probable, and air–fuel mixture can return to be stoichiometric. As exhaust catalytic converters being used more on engines, such conditions of stoichiometric combustion in the engine can be very beneficial to the performance and efficiency of such catalysts.

Conclusion

In this paper several recent studies on bi-fuel engine performance were reviewed and it was noted that for most cases the main attention has been on the mechanical and thermal performances. In the present experimental work, exhaust emission especially as an input to catalytic convertors was also considered.

The synergy effect of combination of CNG with gasoline was investigated on a 1.7 L port injection turbocharged engine. It combines the advantages of each fuel by providing both high volumetric efficiency and strong knocking resistance. So the CNG can act as an octane booster to apply optimal spark timing and substitute for gasoline fuel enrichment, while maintaining nominal performance of a bi-fuel engine. In addition, since stoichiometry can be maintained at full load in mixed case, a conventional three-way catalyst converter will operate efficiently over the whole engine operating range with regard to the stoichiometric lambda window. t was noted that the BSFC decreased by 13% at 3000 rpm full load condition compared to gasoline single fuel mode. It was concluded that the combined injection leads to better performance and more fuel consumption saving.

The experiments showed that because of improvement in knock tendency, the mixed injection of gasoline and CNG is much better than gasoline mode in terms of fuel consumption and unburnt HC and CO emissions. Comparison shows that at 3000 rpm, 30% CNG mass fraction and full-load conditions, BSFC, CO and HC emissions of combination mode are improved by 16, 66 and 50%, respectively, than for gasoline single mode. However, NO_x emission is 69% higher, which may make it difficult to meet the regulation limits for performance of usual catalysts.

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